

# Exclusions on $Z'$ mass and its non-universal couplings in LFV decays

J.A. Orduz-Ducua  
*Departamento de Física,  
 FES-Cuautitlán Izcalli, UNAM  
 C.P. 54740,  
 Estado de México, México.*  
 (Dated: January 12, 2017)

This letter presents a phenomenological analysis for the lepton ( $l_i$ ) decaying into  $l_j l_k \bar{l}_k, l_j \pi^+ \pi^-$  considering family non-universal couplings as source of the lepton flavor-violating (LFV) currents and a new neutral gauge boson ( $Z'$ ) as mediator in the flavor-changing. The most viable  $g_V^{f_i f_j}$  and  $g_A^{f_i f_j}$  couplings are reported as long as derive new bounds for the  $M_{Z'}$  by using current results from LHC and a phenomenological analysis.

## I. INTRODUCTION

We have different motivations to explore lepton sector, taking a new gauge neutral boson as mediator in LFV. We explore new scenarios with flavor-changing neutral currents (FCNC) to obtain bounds for the model parameters [1], and it could imply new physics (NP). The current (or future) colliders could use the data to discard some theoretical models.

One of the simplest model extends the symmetry group of the standard model (SM). This kind of extension introduces an extra symmetry group  $U(1)$ , that is labeled  $U(1)'$  with charge  $\lambda$ . The new symmetry group is:  $\mathcal{G} = SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)'_\lambda$ . In this type of extensions, the scalar sector would have six degree of freedom: four from Higgs doublet, and two from the singlet [2]. However we will consider that the only difference with respect the SM Lagrangian is the introduced potential term and the kinetic term for the singlet field [3, 4].

Nowadays, there are experimental motivations to explore new physics scenarios; e.g., the recent results from CMS and ATLAS collaborations [5, 6] and LHCb preliminary results for  $B^+ \rightarrow K^+ \mu^+ \mu^- (e^+ e^-)$  process have been an incentive to consider family non-universal (FNU) coupling. It will be studied by Babar, Belle (II) and LHCb [7–10].

There are a lot of interesting reports containing physics and phenomenology on  $Z'$  in different contexts [11–17], others that constrain the parameters related to  $Z'$  [18, 19] and several letters on new neutral gauge bosons and Higgs particle [20–23]. Some papers about NP with universal<sup>1</sup> and FNU couplings, which are given by the different values for the fermion couplings, can be found in [25–30] with interesting phenomenological results. Other papers considering FNU couplings for  $B$ -decays are [31–36]. An increasing number of papers considering FNU couplings have appeared recently; e.g., on rare semilepton decays [37], on leptonic channels including neutrinos [38–40], and, even about  $G(221)$  models [41]. There also

are papers considering a new gauge neutral boson coupling to the fermions of the third family [42, 43]. In our paper the  $\theta'$  (mixing angle  $ZZ'$ ) parameter appears in the equations, explicitly. We will fix that parameter respecting the precision measurements imposed, this is:  $\theta' \lesssim 10^{-3}$  [44]. Besides we will use some reports to explore new models as  $E_6$ , Left-Right and others.

In this letter we will analyze the most representative lepton processes in order to constrain the new neutral gauge boson mass and its flavor-changing (FC) non-universal couplings. Basically, we explore the  $g_{V,A}^{f_i f_j}$  parameters which differs from the current literature where  $\epsilon_{L,R}$  chiral coupling are taken ( $g_{V,A} = \epsilon_L \pm \epsilon_R$  [11]). Section II describes the FC for this model in fermion sector and we show the lagrangian for the model. Section III, presents flavor-violating in leptonic sector, and hadron decays. Finally, in section IV we discuss the results and state our conclusions.

## II. ABOUT THE MODEL: LAGRANGIAN

We shall consider a general Lagrangian for fermions and new neutral gauge boson which is very similar to the standard model. In this context, the models could introduce new fermions and new SM fermion charges under the new symmetry group. Then the model obtains FC through: *a*) the mixing of the SM fermions with the new fermions (introduced to avoid anomalies [26, 38]), *b*) the SM fermion charges under the extra group can be FNU [29, 45–47]. We are interested in the second method.

In the next subsections we consider different scenarios which have a pedagogical motivation and we assume to respect the CKM bounds.

### A. Lagrangian for the family universal model

In a family universal model, the vertex  $\bar{f} f Z'$  is proportional to fermion charges:

<sup>1</sup> Flavor violation could be suppressed if the charges are family universal (FU) [24].

### C. Sample in the lepton sector

We recall the Lagrangian for the neutral currents sector, which is considered [26, 49–51]:

$$-\mathcal{L}_{CN} = \sum_f g_1 \bar{\psi}_{f_i} \gamma^\mu (g_V^f - g_A^f \gamma^5) \psi_{f_i} Z_\mu^1 + \sum_{f_i, f_j} g'_1 \bar{\psi}_{f_i} \gamma^\mu (g_V^{f_i f_j} - g_A^{f_i f_j} \gamma^5) \psi_{f_j} Z_\mu^2 \quad (1)$$

where  $\psi_f$  and  $\psi_{f_i}$  are the weak gauge eigenstates.  $\tilde{g}_{V,A}^f$  are the vector and axial-vector associated to the  $\bar{f}fZ$ ; and  $\tilde{g}_A^{f_i f_j}$  those associated to couplings  $\bar{f}fZ'$  vertex, and we will consider  $g_1 = \frac{g}{\cos \theta_W}$ .  $Z_\mu^1, Z_\mu^2$  are the gauge eigenstates associated to  $Z$  and  $Z'$  through

$$Z_\mu^1 = Z_\mu \cos \theta' + Z'_\mu \sin \theta', \\ Z_\mu^2 = -Z_\mu \sin \theta' + Z'_\mu \cos \theta',$$

respectively. We can re-write the eq. (1) as:

$$-\mathcal{L}_{CN} = g_1 \left( \cos \theta' J_1^\mu + \frac{g'_1}{g_1} \sin \theta' J_2^\mu \right) Z_\mu + g_1 \left( -\sin \theta' J_1^\mu + \frac{g'_1}{g_1} \cos \theta' J_2^\mu \right) Z'_\mu \quad (2)$$

where  $\theta'$  is the mixing angle  $Z - Z'$  and

$$J_1^\mu = \sum_f \bar{\psi}_f \gamma^\mu (g_V^f - g_A^f \gamma^5) \psi_f \\ J_2^\mu = \sum_{f_i, f_j} g'_1 \bar{\psi}_{f_i} \gamma^\mu (g_V^{f_i f_j} - g_A^{f_i f_j} \gamma^5) \psi_{f_j}$$

The eq. (2) shows the explicit dependence with  $g_{V,A}^{f_i f_j}$ . Now on we consider the neutral current sector for  $Z'$ , so we will neglect the prime label. Now we have a sector

- with non-universal couplings and
- proportional to the charges  $q_\lambda$  through  $g_{V,A}^{f_i f_j}$ .

### III. PHENOMENOLOGY: LEPTON AND HADRON SECTOR

We obtained the decay width<sup>3</sup> using FeynCalc package [53]; namely,

$$\Gamma(l_i \rightarrow l_j l_k \bar{l}_k) = \frac{g_1^4 m_{l_i} r_{l_i Z'}^2 \sec^4 \theta'}{768 \pi^3} \times \left( 13 \mathcal{F}_1 (g_V^{l_k^2} + g_A^{l_k^2}) + 12 \mathcal{F}_2 g_V^{l_k} g_A^{l_k} \right) \quad (3)$$

$$\mathcal{L}^{FU} \propto (\bar{f}_1^0 \ \bar{f}_2^0 \ \bar{f}_3^0)_L \gamma^\mu \begin{pmatrix} Q_L & 0 & 0 \\ 0 & Q_L & 0 \\ 0 & 0 & Q_L \end{pmatrix} \begin{pmatrix} f_1^0 \\ f_2^0 \\ f_3^0 \end{pmatrix}_L Z'_\mu$$

We consider a rotation to the mass eigenstates  $f_L = V_L f_L^0$ , where  $f_L^0 = \begin{pmatrix} f_1^0 \\ f_2^0 \\ f_3^0 \end{pmatrix}_L$  ( $f^0$  means interaction eigenstates) and  $V_L$  is a orthogonal transformation matrix; e.g.:

$$V = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & s_{13} \\ -c_{23}s_{12} - c_{12}s_{13}s_{23} & c_{12}c_{23} - s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s_{12}s_{23} - c_{12}c_{23}s_{13} & -c_{23}s_{12}s_{13} - c_{12}s_{23} & c_{13}c_{23} \end{pmatrix}$$

where  $c_{ij} = \cos \theta_{ij}$  and  $s_{ij} = \sin \theta_{ij}$ . Then:

$$\mathcal{L}^{FU} \propto (\bar{f}_1 \ \bar{f}_2 \ \bar{f}_3)_L \gamma^\mu Q_L V_L^\dagger \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix} V_L \begin{pmatrix} f_1 \\ f_2 \\ f_3 \end{pmatrix}_L Z'_\mu$$

where  $Q_L$  is the family universal coupling. If the charges are same, matrix  $\mathbf{Q} = (V_L^\dagger I V_L)$  is diagonal and there is not mixing.

### B. Lagrangian for the family non-universal model

In this subsection, we present the way the non-universal couplings generate the flavor-change, namely:

$$\mathcal{L}^{FNU} \propto (\bar{f}_1^0 \ \bar{f}_2^0 \ \bar{f}_3^0)_L \gamma^\mu \begin{pmatrix} Q_L & 0 & 0 \\ 0 & Q'_L & 0 \\ 0 & 0 & Q''_L \end{pmatrix} \begin{pmatrix} f_1^0 \\ f_2^0 \\ f_3^0 \end{pmatrix}_L Z'_\mu.$$

As before, we obtain,

$$\mathcal{L}^{FNU} \propto (\bar{f}_1 \ \bar{f}_2 \ \bar{f}_3)_L \gamma^\mu V_L^\dagger \begin{pmatrix} Q_L & 0 & 0 \\ 0 & Q'_L & 0 \\ 0 & 0 & Q''_L \end{pmatrix} V_L \begin{pmatrix} f_1 \\ f_2 \\ f_3 \end{pmatrix}_L Z'_\mu.$$

Charges are family non-universal and the matrix  $\mathbf{Q}$  is not diagonal. this scenario is interesting to explore the FC mediated by new neutral gauge boson.

We will explore models with FNU couplings with gauge group given by:  $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_\lambda$ . We labeled  $q_\lambda$  as the SM fermion charges under  $U(1)_\lambda$ , these are family-depending. We could have  $Z'$  effects if we suppose  $M_{Z'} \lesssim 2 \text{ TeV} - 3 \text{ TeV}$ , and these could be detectable in LHC or in future colliders<sup>2</sup>.

<sup>2</sup> Nowadays, there have been interesting results for bosons with masses around sub-GeV as shown in ref. [48].

<sup>3</sup> Similar results can be found in [26, 27, 52]

where  $r_{ij} = \frac{m_i^2}{m_j^2}$ , and  $\mathcal{F}_1 = g_A^{l_i l_j^2} + g_V^{l_i l_j^2}$ ,  $\mathcal{F}_2 = g_V^{l_i l_j} g_A^{l_i l_j}$  function contain the FC-parameters. This result shows the symmetry-conserving under  $g_V$  and  $g_A$ , and the dependence with the model parameters ( $g'_1, M'_{Z'}$  and  $\theta'$ ), explicitly.

The next two subsections, we will explore the lepton decays to three lepton in the final states. The third subsection explores pair of pions in the final state and some parameter space in hadron process.

### A. $\tau^- \rightarrow \mu^- \mu^+ \mu^-$ decay

We will explore the process represented in fig. 1.

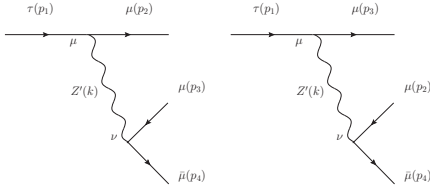


FIG. 1: Feynman diagram and its adjoint for muons in the final state.

The decay width is given by eq. (3), considering  $l_i = \tau^-$  and  $l_j = l_k = \mu^-$ . We shall explore some cases for the parameters. We include the experimental data and some phenomenological results in models with new neutral gauge boson.

We have explored two cases: I)  $g'_1 = g_{EW}$ . In this case we obtain constraints on  $Z'$  mass for different models (see fig. 2). Figure 2 shows the  $\text{Br}(\tau^- \rightarrow \mu^- \mu^+ \mu^-)$ , we have plotted 331 models,  $E_6$  models  $Z'_\chi$ ,  $Z'_\psi$  and  $Z'_\eta$  with  $\alpha = 0, \pi/2, \arctan(-\sqrt{5/3})$ , respectively; where  $\alpha$ -parameter is an angle to define the symmetry breaking pattern of the  $E_6$  models. Left-Right (LR) and alternative Left-Right (ALR) models; and the horizontal line represents the experimental bound.

The recent results for the  $\text{Br}(\tau^- \rightarrow \mu^- \mu^+ \mu^-) = 2.1 \times 10^{-8}$  constrains the Br's for the models; then we calculated the limits for the  $M_{Z'}$  in several models those values are shown in table I. We consider the experimental bounds and extract the lower masses for the new neutral gauge boson, and obtain limits for this parameter.

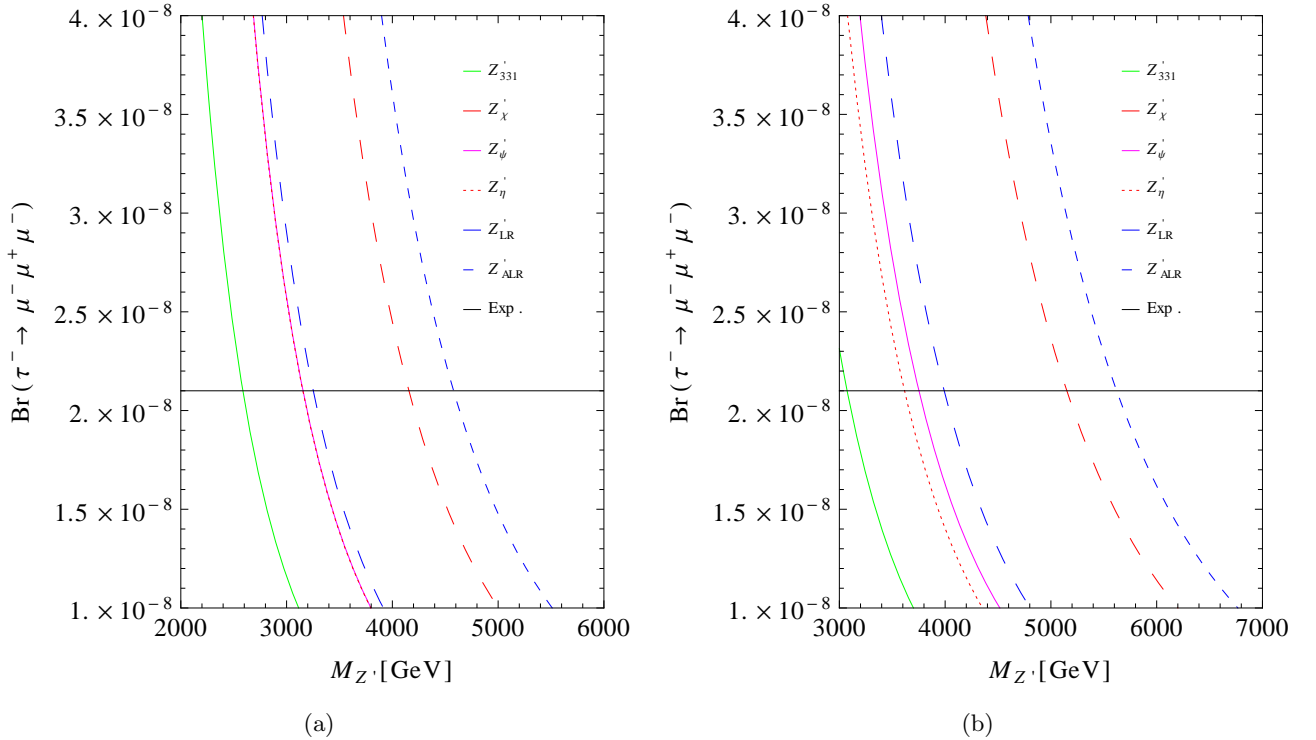


FIG. 2: Branching ratios for the  $\tau \rightarrow \mu^- \mu^+ \mu^-$ . We chose for a)  $g_V^{f_i f_j} = 1 \times 10^{-1}$ ,  $g_A^{f_i f_j} = 1 \times 10^{-3}$  and b)  $g_V^{f_i f_j} = 1 \times 10^{-1}$ ,  $g_A^{f_i f_j} = 1 \times 10^{-1}$ . We have taken  $\theta' = 1 \times 10^{-3}$  for each case.

We use the previous analysis, and found limits over the  $Z'$  mass, those results can be found in the table I. This table shows two scenarios: first row: we chose an asymmetric scenario where the FC-couplings are different by two orders of magnitude. Second row: we chose a symmetric scenario where both FC-couplings are same order of magnitude. Figs. 2a shows the asymmetric scenario and fig. 2b shows the symmetric scenario, we have explored different modes with  $Z'$ . We found differences in the mass scale of the new neutral gauge boson.

TABLE I: Low allowed mass for  $Z'$  in different models. The first row shows the mass values for fig. 2a and the second row shows the mass values for fig. 2b. We used the couplings given in ref. [54].

	$Z'_{331}$	$Z'_\eta$	$Z'_\psi$	$Z'_{LR}$	$Z'_\chi$	$Z'_{ALR}$
$M_{Z'} \text{ (GeV)}$	2446.2	2984.4	3061.4	3085.7	4025.3	4446.1
$M_{Z'} \text{ (GeV)}$	3056.3	3622.9	3731.4	3976.9	5160.7	5636.3

For the case II)  $g'_1 = 0.105$  taken from [26]. This case works to constrain every model since  $M_{Z'} < 900 \text{ GeV}$  and this mass range is excluded for experiments [55].

Next part shows the phenomenology results for the leptonic processes mediated by a new neutral gauge boson.

### B. $\mu^- \rightarrow e^- e^+ e^-$ decay

The Feynman diagram for this process is shown in fig. 3. The decay width is given by eq. (3), considering  $l_i = \mu^-$  and  $l_j = l_k = e^-$ .

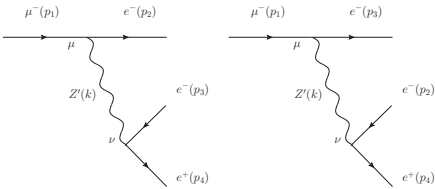


FIG. 3: Feynman diagram and its adjoint for electrons in the final state.

From the constraints the last section we explore the  $\mu^- \rightarrow e^- e^+ e^-$ . We found  $g_{V,A}^{e\mu} \sim \mathcal{O}(10^{-4})$ , it can see on fig. 4 where the green region is favored.

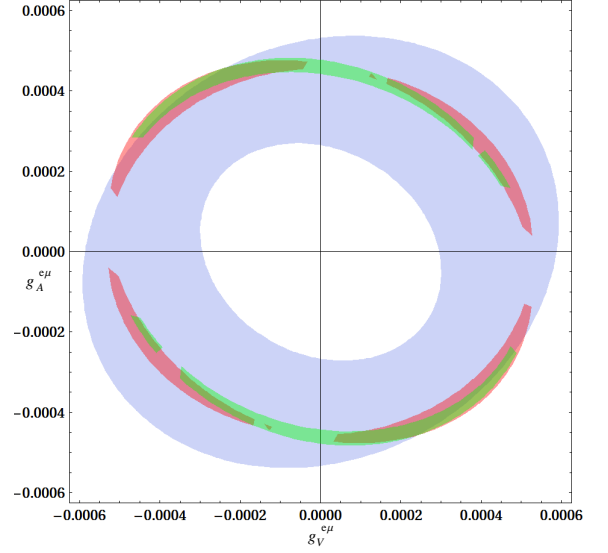


FIG. 4:  $g_V^{fi fj}$  vs.  $g_A^{fi fj}$  using the table I. Regions among curves, which contain the allowed values for the  $g_{V,A}^{fi fj}$  parameters. Green region would contain the advantaged  $g_{V,A}^{e\mu}$  values.

We imposed the constraints, and plotted region, and used the  $M_{Z'}$  values from the table I. In fig. 4 shows the regions for the different models with a new neutral gauge boson. The green region could bound the interesting values for the  $g_A^{e\mu} - g_V^{e\mu}$  parameters.

### C. The process in the hadron sector

We have taken motivations from recent experimental results, which give constraints for the hadron and lepton in the final states:  $\text{Br}(\tau^- \rightarrow \mu^- \pi^+ \pi^-) = 10^{-7}, 10^{-6}, 10^{-5}$  for Belle, BaBar and CLEO, respectively [56]. Even more we expect Belle II has surprising physical results when it achieves high luminosity (in 2022), this is 50 times more than Belle [57].

The hadronic pair ( $\pi^+ \pi^-$ ) is produced, at the beginning, in a initial state no hadrons  $\langle \pi^+(p_4) \pi^-(p_3) | \bar{Q} \gamma_\mu q | 0 \rangle$ , where  $Q$  and  $q$  are light quarks ( $u, d, s$ ). The weak current has the form [58]:

$$\langle \pi^+(p_4) \pi^-(p_3) | \left[ \frac{b_1}{2} (\bar{u} \gamma^\mu u - \bar{d} \gamma^\mu d) + \frac{b_2}{2} (\bar{u} \gamma^\mu u + \bar{d} \gamma^\mu d) \right] | 0 \rangle \quad (4)$$

but the second term has not contribution because of the G-parity. We have used  $\frac{1}{2}(b_1 + b_2) = a_{uu}$  and  $\frac{1}{2}(-b_1 + b_2) = a_{dd}$ , with  $a_{uu, dd}$  are couplings associated to each state  $u\bar{u}, d\bar{d}$ . Then the hadron element matrix is given by:

$$\langle \pi^+(p_4) \pi^-(p_3) | \frac{1}{2} (\bar{u} \gamma^{\mu_2} u - \bar{d} \gamma^{\mu_2} d) | 0 \rangle = F_\pi(q^2) (p_4 - p_3)^{\mu_2}$$

where  $q^2 = (p_4 + p_3)^2$ ,  $F_\pi(q^2) = \frac{m_\rho^2}{m_\rho^2 - q^2 - im_\rho \Gamma_\rho}$  and  $m_\rho = 775 \text{ MeV}$ ,  $\Gamma_\rho = 150 \text{ MeV}$  [59]. The form factor,  $F_\pi(q^2)$ , is the most simple, and useful form to use in our model, other forms can be found in refs. [60–63].

The Feynman diagram for the process  $\tau^- \rightarrow \mu^- \pi^+ \pi^-$  is shown by fig. 5. The total amplitud is given by,

$$\mathcal{M} = F_\pi(q^2) (p_4 - p_3)^{\mu_2} \Pi_{Z'}^{\mu_1 \mu_2} \bar{u}(p_2) g_{Z' \tau \mu}^{\mu_1} u(p_1) \quad (5)$$

where  $\Pi_{Z'}^{\mu_1 \mu_2} = -g^{\mu_1 \mu_2} / (k^2 - M_{Z'}^2)$  and  $g_{Z' \tau \mu}^{\mu_1} = \gamma^{\mu_1} (g_V^{f_i f_j} - g_A^{f_i f_j} \gamma^5)$ . In this letter we will use  $k^2 \ll M_{Z'}^2$ . Taking  $r_{\pi\tau} = \frac{m_{\pi^\pm}^2}{m_\tau^2} \rightarrow 0$  and  $r_{\mu\tau} \rightarrow 0$ , we obtained the eq. (6) for the decay width; this is,

$$\frac{d\Gamma(\tau^- \rightarrow \mu^- \pi^+ \pi^-)}{dx dy} = \frac{m_\tau}{128\pi^3} \frac{r_{\tau Z'}^2 r_{\rho\tau}^2 \mathcal{F}_{VA}^{ij} \mathcal{G}}{\mathcal{H}} \quad (6)$$

where  $\mathcal{F}_{VA}^{ij} = g_V^{f_i f_j^2} + g_A^{f_i f_j^2}$ , depends on the FC-parameters; and  $\mathcal{G} = x^2 + 3x(y-1) + 4(y-1)^2$ ,  $\mathcal{H} = r_\rho^2 + \left(\frac{\Gamma_\rho^2}{m_\tau^2} + 2y - 2\right) r_{\rho\tau} + (y-1)^2$  contains the variables of integration; and  $r_{ij} = \frac{m_i^2}{m_j^2}$ . The  $x$  and  $y$  are variables:  $1-x < y < 1+x$ ,  $0 < x < 1$ .

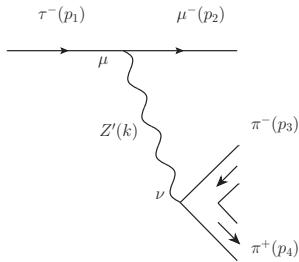


FIG. 5: The Feynman diagram for the  $\tau^- \rightarrow \mu^- \pi^+ \pi^-$  process.

We use the constraints given in [55] and the results is shown in fig. 6. In this process we found that the lowest mass is  $M_{Z'} \sim 1600 \text{ GeV}$ , considering the lepton flavor-changing,  $\tau \rightarrow \mu$  and some representative values for the couplings, since eq. (6) depends on  $g_{V,A}^{f_i f_j}$  parameters.

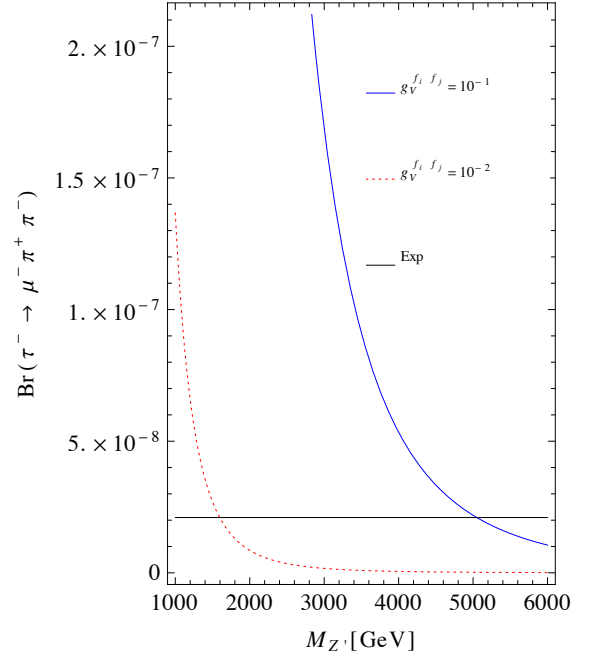


FIG. 6: Branching ratio for the processes  $\tau^- \rightarrow \mu^- \pi^+ \pi^-$ . We show an optimistic  $g_V^{f_i f_j}$  value, and we have chosen  $g_A^{f_i f_j} = 1 \times 10^{-4}$  for both of them.

We explore the parameter space in the  $\tau^- \rightarrow \mu^- \pi^- \pi^+$  process mediated by a neutral gauge boson. We obtained the region for  $M_{Z'}$  in fig. 7. This figure shows the allowed region for the vector coupling considering the flavor-changing mediated by a  $Z'$  coming from different models; our results show wider region for high  $Z'$  masses. We expect interesting results for the next generation of colliders.

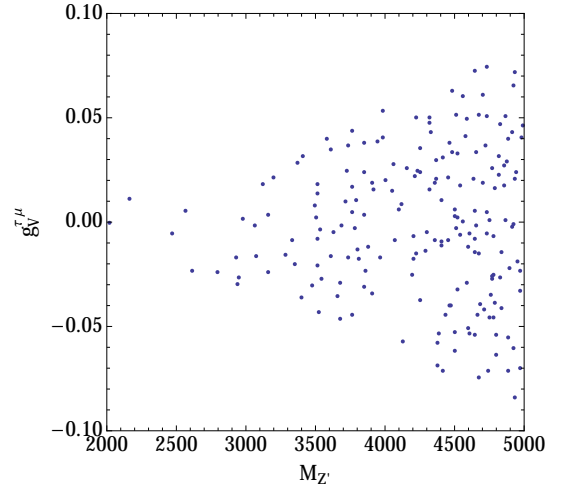


FIG. 7: Scattering plot for the FC-parameters,  $M_{Z'}$ , and Br for the  $\tau^- \rightarrow \mu^- \pi^+ \pi^-$  process.

We considered the  $g_A^{\tau\mu}$ -parameter versus  $M_{Z'}$ , and the result was very similar what was shown in fig. 7.

#### IV. DISCUSSION AND CONCLUSIONS

In this letter we explore some models with a  $Z'$  which has family non-universal coupling in processes with FC as  $\tau^- \rightarrow \mu^- \mu^+ \mu^-$  and  $\mu^- \rightarrow e^- e^+ e^-$ , and the  $\tau^- \rightarrow \mu^- \pi^+ \pi^-$  process (hadronic process). We have obtained estimation for the  $Z'$  mass and its parameter, and considering the current experimental results, we found some representative values for the  $M_{Z'}$  and regions for the parameters, which contains the FNU charges. I am aware that this is a simple method to get bounds, however it works to give a nominal values for the  $Z'$  mass which obey the experimental constraints.

Figure 2 shows a excluded mass range for different models in lepton processes considering FC, this mass range could be explored for next colliders. From the  $\tau^- \rightarrow \mu^- \mu^+ \mu^-$  process, we report  $M_{Z'} \gtrsim 2500$  GeV for  $g_1' = g_{EW}$  (gauge coupling) and  $g_V^{f_i f_j} = 10^{-1}$ ,  $g_A^{f_i f_j} = 10^{-3}$  or viceversa, since equations are symmetrical under  $g_V^{f_i f_j} \leftrightarrow g_A^{f_i f_j}$ . For the process  $\mu^- \rightarrow e^- e^+ e^-$ , we note  $M_{Z'} \gtrsim 3000$  GeV for  $g_{V,A}^{f_i f_j} \lesssim 10^{-4}$ ; and from  $\tau^- \rightarrow \mu^- \pi^+ \pi^-$  process, we found  $M_{Z'} \gtrsim 5000$  GeV, considering  $g_V^{f_i f_j} = 10^{-1,-2}$  and  $g_A^{f_i f_j} = 10^{-4}$ .

We regard the experimental bounds for the  $l_i \rightarrow l_i l_j \bar{l}_k$  process, which restrict the parameter space (see fig. 4): the bounded region for the overlapping gives the most interesting values for the vector and vector-axial couplings, considering FC in lepton process. Exploring the hadron processes, we also exclude a mass range, figure 6. The

excluded regions are consistent with the experimental results [64], see table I.

Figure 7 shows the allowed region considering the current experimental results for the  $\tau^- \rightarrow \mu^- \pi^+ \pi^-$  process. We found a similar region for the  $g_A^{\tau\mu}$ -parameter. In general, this plot reveals the  $M_{Z'}$  values for the coupling with FC. In this scenarios with new physics, correlation between those parameters could give more information about the FC in the hadron sector.

Using the recent results from LHC, we have constrained the  $g_{V,A}^{f_i f_j}$  parameters, besides found the lowest mass allowed for a  $Z'$  coming from some models, considering flavor-changing neutral currents, family non-universal coupling; and a process comes from hadron sector. Though we report high mass limits for a new neutral gauge boson, we are optimistic about the next LHC results as well as the future generation colliders.

#### ACKNOWLEDGMENTS

This work was supported by postdoctoral scholarships at DGAPA-UNAM and SNI (Conacyt). I thank G. López Castro for the discussions about physics; I would also like to thank P. Roig, M.A. Pérez-Angón and R. Gaitán Lozano for reading this manuscript, and A. Courtoy for providing comments and refs. [61, 62, 65].

**Final remarks:** I want to share several preprints on FC and new boson phenomenology uploaded while I was writing this manuscript: [66–71].

- 
- [1] D. A. Demir, G. L. Kane, and T. T. Wang, Phys.Rev. **D72**, 015012 (2005), hep-ph/0503290.
  - [2] L. Basso, A. Belyaev, S. Moretti, and G. M. Pruna, Phys. Rev. **D81**, 095018 (2010), 1002.1939.
  - [3] L. Basso, A. Belyaev, S. Moretti, G. M. Pruna, and C. H. Shepherd-Themistocleous, Eur. Phys. J. **C71**, 1613 (2011), 1002.3586.
  - [4] L. Basso, A. Belyaev, S. Moretti, G. M. Pruna, and C. H. Shepherd-Themistocleous, PoS **EPS-HEP2009**, 242 (2009), 0909.3113.
  - [5] C. Collaboration (CMS), **CMS-PAS-EXO-15-004** (2015).
  - [6] G. Aad et al. (ATLAS), Phys. Rev. Lett. **115**, 031801 (2015), arXiv: 1503.04430. Report **ATLAS-CONF-2015-081**. Search for resonances decaying to photon pairs in  $3.2 \text{ fb}^{-1}$  of  $pp$  collisions at  $\sqrt{s} = 13$  TeV with the ATLAS detector.
  - [7] *Conference LHCP 2014. See web public site LHCb* <http://lhcb-public.web.cern.ch/lhcb-public/>, the conference <http://www.bnl.gov/lhcp2014/index.php> and the page on indico (contribution's list): <https://indico.cern.ch/event/279518/contributions> (2014), conference administrator: Winnie Yu.
  - [8] BaBar. Web site for the collaboration: <http://www.slac.stanford.edu/BF/>.
  - [9] Belle. Web site for the collaboration: <http://belle.kek.jp/>.
  - [10] CLEO. Web site for the collaboration: <http://www.lns.cornell.edu/public/CLEO/>.
  - [11] P. Langacker, Rev.Mod.Phys. **81**, 1199 (2009), 0801.1345.
  - [12] P. Langacker, AIP Conf.Proc. **1200**, 55 (2010), 0909.3260.
  - [13] A. Leike, Phys.Rept. **317**, 143 (1999), hep-ph/9805494.
  - [14] J. Erler and P. Langacker, Phys.Lett. **B456**, 68 (1999), hep-ph/9903476.
  - [15] A. Abada, D. Becirevic, M. Lucente, and O. Sumensari (2015), 1503.04159.
  - [16] P. Bandyopadhyay and E. J. Chun (2014), 1412.7312.
  - [17] A. Crivellin, G. D'Ambrosio, and J. Heeck, Phys. Rev. **D91**, 075006 (2015), 1503.03477.
  - [18] A. Kundu, Phys.Lett. **B370**, 135 (1996), hep-ph/9504417.
  - [19] J. Erler, P. Langacker, S. Munir, and E. Rojas, JHEP **0908**, 017 (2009), 0906.2435.
  - [20] L. Edelhäuser and A. Knochel (2014), 1408.0914.
  - [21] H.-L. Li, Z.-G. Si, X.-Y. Yang, Z.-J. Yang, and Y.-J. Zheng, Phys.Rev. **D87**, 115024 (2013), 1305.1457.
  - [22] J. L. Diaz-Cruz, J. M. Hernández-López, and J. A. Orduz-Ducua, J.Phys. **G40**, 125002 (2013), 1304.0016.
  - [23] J. Hernández López and J. Orduz-Ducua, J.Phys.Conf.Ser. **468**, 012012 (2013).

- [24] P. Langacker, G. Paz, L.-T. Wang, and I. Yavin, *Phys.Rev.* **D77**, 085033 (2008), 0801.3693.
- [25] J. Bernabeu, E. Nardi, and D. Tommasini, *Nucl.Phys.* **B409**, 69 (1993), hep-ph/9306251.
- [26] P. Langacker and M. Plumacher, *Phys.Rev.* **D62**, 013006 (2000), hep-ph/0001204.
- [27] C.-W. Chiang, Y.-F. Lin, and J. Tandean, *JHEP* **1111**, 083 (2011), 1108.3969.
- [28] V. Barger, L. Everett, J. Jiang, P. Langacker, T. Liu, et al., *Phys.Rev.* **D80**, 055008 (2009), 0902.4507.
- [29] V. Barger, L. L. Everett, J. Jiang, P. Langacker, T. Liu, et al., *JHEP* **0912**, 048 (2009), 0906.3745.
- [30] A. Arhrib, K. Cheung, C.-W. Chiang, and T.-C. Yuan, *Phys.Rev.* **D73**, 075015 (2006), hep-ph/0602175.
- [31] V. Barger, C.-W. Chiang, J. Jiang, and P. Langacker, *Phys. Lett.* **B596**, 229 (2004), hep-ph/0405108. V. Barger, C.-W. Chiang, P. Langacker and H.-S. Lee, *Phys. Lett.* **B598**, 218-226 (2004), hep-ph/0406126. C.-W. Chiang N. G. Deshpande, and J. Jiang, *Phys. Lett.* **B652**, 285-291 (2007), hep-ph/0604223. **08**, 075 (2006), hep-ph/0606122. *Chin. Phys.* **C36** 14-24 (2012), arXiv: 0911.2399X. G. He, and G. Valencia, *Phys. Rev.* **D93** 074003 (2016), arXiv: 1601.07328.
- [32] Q. Chang, X.-Q. Li, and Y.-D. Yang, *J.Phys.* **G41**, 105002 (2014), 1312.1302.
- [33] Y. Li, J. Hua, and K.-C. Yang, *Eur.Phys.J.* **C71**, 1775 (2011), 1107.0630.
- [34] B. B. Sirvanli, *Phys.Rev.* **D89**, 095016 (2014), 1306.6461.
- [35] D. Bečirević, O. Sumensari, and R. Zukanovich Funchal, *Eur. Phys. J.* **C76**, 134 (2016), 1602.00881.
- [36] A. K. Alok, S. Baek, and D. London, *JHEP* **07**, 111 (2011), 1010.1333.
- [37] Q. Chang and Y.-H. Gao, *Nucl.Phys.* **B845**, 179 (2011), 1101.1272.
- [38] H. La (2013), 1308.0088.
- [39] A. N. Khan, *Phys. Rev.* **D93**, 093019 (2016), 1605.09284.
- [40] C.-W. Chiang, G. Faisel, Y.-F. Lin, and J. Tandean, *JHEP* **10**, 150 (2013), 1204.6296.
- [41] K. Hsieh, K. Schmitz, J.-H. Yu, and C.-P. Yuan, *Phys.Rev.* **D82**, 035011 (2010), 1003.3482.
- [42] B. Holdom, *Phys.Lett.* **B666**, 77 (2008), 0805.1965.
- [43] J. Erler and P. Langacker, *Phys.Rev.Lett.* **84**, 212 (2000), hep-ph/9910315.
- [44] P. Abreu et al. (DELPHI Collaboration), *Z.Phys.* **C65**, 603 (1995).
- [45] G. Cleaver, M. Cvetič, J. Espinosa, L. Everett, P. Langacker, et al., *Phys.Rev.* **D59**, 115003 (1999), hep-ph/9811355.
- [46] G. Cleaver, M. Cvetič, J. R. Espinosa, L. L. Everett, and P. Langacker, *Nucl.Phys.* **B525**, 3 (1998), hep-th/9711178.
- [47] M. Masip and A. Pomarol, *Phys.Rev.* **D60**, 096005 (1999), hep-ph/9902467.
- [48] J. Heeck, *Phys. Lett.* **B758**, 101 (2016), 1602.03810.
- [49] P. Langacker and M.-x. Luo, *Phys. Rev.* **D45**, 278 (1992).
- [50] U. Amaldi, A. Bohm, L. S. Durkin, P. Langacker, A. K. Mann, W. J. Marciano, A. Sirlin, and H. H. Williams, *Phys. Rev.* **D36**, 1385 (1987).
- [51] A. A. Andrianov, P. Osland, A. A. Pankov, N. V. Romanenko, and J. Sirkka, *Phys. Rev.* **D58**, 075001 (1998), hep-ph/9804389.
- [52] C.-X. Yue, Y.-M. Zhang, and L.-J. Liu, *Phys. Lett.* **B547**, 252 (2002), hep-ph/0209291.
- [53] R. Mertig, M. Bohm, and A. Denner, *Comput. Phys. Commun.* **64**, 345 (1991).
- [54] C.-X. Yue and M.-L. Cui, *Nucl.Phys.* **B887**, 371 (2014), 1408.2647.
- [55] J. Beringer et al. (Particle Data Group), *Phys.Rev.* **D86**, 010001 (2012).
- [56] Y. Amhis et al. (Heavy Flavor Averaging Group) (arXiv: 1207.1158. 2012), 1207.1158.
- [57] T. Abe et al. (Belle-II Collaboration) (arXiv: 1011.0352. 2010), Pavel Pakhlov. Physics with the Belle detector *EPJ Web Conf.* 72:00019, 2014. See Belle's II web site: <http://belle2.kek.jp/> and the KIT's web site: <https://www.ekp.kit.edu/english/belle2.php> , 1011.0352.
- [58] F. Flores-Baez, A. Flores-Tlalpa, G. Lopez Castro, and G. Toledo Sanchez, *Phys.Rev.* **D74**, 071301 (2006), hep-ph/0608084.
- [59] P. P. L. B, Review of Particle Physics (July 2012).
- [60] A. Flores-Tlalpa, G. Lopez Castro, and G. Sanchez Toledo, *Phys.Rev.* **D72**, 113003 (2005), hep-ph/0511315.
- [61] M. Diehl, T. Feldmann, P. Kroll, and C. Vogt, *Phys.Rev.* **D61**, 074029 (2000), hep-ph/9912364.
- [62] M. V. Polyakov, *Nucl.Phys.* **B555**, 231 (1999), hep-ph/9809483.
- [63] P. Roig, *Nucl. Phys. Proc. Suppl.* **225-227**, 161 (2012), 1112.0962.
- [64] K. A. Olive et al. (Particle Data Group), *Chin. Phys.* **C38**, 090001 (2014).
- [65] W. Altmannshofer, C.-Y. Chen, P. S. B. Dev, and A. Soni (2016), 1607.06832.
- [66] V. Khachatryan et al. (CMS), *Phys. Lett.* **B749**, 337 (2015), 1502.07400.
- [67] J. Fuentes-Martin, *PoS EPS-HEP2015*, 577 (2015), 1511.00355.
- [68] S. Banerjee, M. Mitra, and M. Spannowsky, *Phys. Rev.* **D92**, 055013 (2015), 1506.06415.
- [69] O. M. Boyarkin and G. G. Boyarkina, *Int. J. Mod. Phys.* **A31**, 1650005 (2016).
- [70] A. Gutiérrez-Rodríguez and M. A. Hernández-Ruiz, *Adv. High Energy Phys.* **2015**, 593898 (2015), 1506.07575.
- [71] C. S. Kim, X.-B. Yuan, and Y.-J. Zheng, *Phys. Rev.* **D93**, 095009 (2016), 1602.08107.